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Buffered Explosions in Steel Pressure Vessels

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DESCRIPTION

We consider the problem of a strong explosion surrounded by a porous compacting buffer medium, consisting of solid, incompressible particles separated by void space. The buffer medium is idealized to be separated from the explosion products by an impermeable membrane so that Rayleigh-Taylor instability, and consequent interpenetration, is neglected. The entire system is assumed to be contained in a thin-walled spherical pressure vessel, the stress in the walls of which we seek to minimize. The compaction behind the shock front in the buffer medium is taken to be uniform, and the strength of the porous material is assumed to be negligible in comparison to the compressibility of the fully compacted medium. If the impulse is delivered uniformly to the walls of the vessel, and the explosive debris behaves as a perfect gas, it has been shown [1] that the peak hoop stress is given by:

$$S \equiv \frac{\sigma_{\theta m}\delta}{P_e R} = \frac{2\left[(X/\omega+1)^{1+\alpha-\gamma}-1\right]}{3(1+\alpha-\gamma)(1-k^{1/3})(X/\omega)^{\alpha}} \tag{1}$$

where δ and R are respectively the wall thickness and sphere radius, X is the buffer-

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to-explosive mass ratio, $k = 1 - \rho_{00}/\rho_0$, $\omega = \rho_{00}/k\rho_D$, and γ is the ratio of specific heats of the expanded explosion products. ρ_{00} is the initial density of the buffer, ρ_0 is the compacted density behind the shock front, and ρ_D is the density of the explosive. The equilibrium pressure, $P_e = 3(\gamma - 1)W/4\pi R^3$, generated by the explosive yield W, is used to normalize the stress. The parameter α is the fractional dissipation. Although material at rest acquires, in a strong shock wave, the same kinetic and internal energies per unit mass, there is experimental evidence that substantially less dissipation actually occurs in the compaction process; α was therefore introduced to measure the discrepancy.

EXPERIMENTS

Salt and "Snow" Buffers

In a series of unpublished experiments, performed during the three year period beginning in the fall of 1958, W. B. Crowley of our laboratory measured the hoop strain in a collection of thin-walled spherical pressure vessels subjected to explosive loading. Small spherical charges of PBX 9404 were centrally located in the spheres and surrounded either with air, salt, or "snow" (actually finely shaved ice, sufficiently subcooled to avoid melting during shaving and loading). The steel vessels employed varied from 1-ft to 4-ft in diameter, and at least eight wire-strain-gages were used for each test.

Figure 1 compares the results obtained with air- and salt buffers. The charge parameter

$$\varsigma \equiv \frac{\rho_{00}}{\rho_A} \frac{m_D}{m_0} \tag{2}$$

permits a representation of the data on the same graph. ρ_A is the density of air at STP so that ς is approximately the ratio of the charge mass, m_D, to the mass of air that would fill a sphere with volume just sufficient to hold the buffer mass m_0.

Each symbol in the figure represents the peak stress determined by averaging the output of the several gages attached to a given sphere. The filled-in symbols depict the salt results. For the salt, and over the entire domain of ς investigated, S is seen to remain approximately constant at a value of about 1.5. We note that

$S = 2$ is the expected value of S if only the equilibrium pressure, P_e, is applied in stepwise fashion. The solid curves marked α are derived from equation (1). In order to evaluate this expression, both the loading density ($\rho_{00} = 1.18$ g/cm^3) and the density of the compacted salt (ρ_0) are required. Unfortunately, the latter was not measured in the experiments although the salt was compacted into a hard layer which adhered to the spherical wall, and which was removed only with difficulty by a combination of dissolution and mechanical means. The curves in Figure 1 are based on compaction to 76% of theoretical density (2.13 g/cm^3). Even if fully compacted material was derived, however, the fractional dissipation would not vary much. For example, the experiments portrayed in Figure 1 show that $S \approx 1.45$ at $\varsigma = 0.9$. At 76% of theoretical density, equation (1) yields $\alpha = 0.46$; at 100% , $\alpha = 0.59$. The same range of α was determined from a series of impulse experiments performed with carbon powder [1].

Figure 1 also shows that the salt is much more effective than air as a buffer, especially at low values of ς. The air data exhibit a much wider scatter but are mostly contained between simply derived theoretical bounds on S. For a bare charge surrounded by void, an upper bound on S is:

$$S_V = [E/(1-\nu)\rho_w e_D]^{1/2}/3(\gamma - 1) \tag{2}$$

where E and ν are respectively the Young's modulus and Poisson's ratio for the containing vessel with density ρ_w, and e_D is the specific explosion energy. Equation (2) assumes the explosion products behave as a perfect gas, that the impulse delivery period is small compared with the eigenperiod of the vessel, and neglects rebound effects. This is the basis for the horizontal dashed line in Figure 1. The dashed curve labeled air blast theory derives from Chernyi's approximate treatment for a strong explosion surrounded by a perfect gas medium [2]:

$$S_A = S_V \left\{ 1 + \left[\frac{2(\gamma-1)}{3\gamma-1}\frac{m_0}{m_D}\right]^{1/2} \right\} \tag{3}$$

where m_0 here is the mass of the shock-heated air (whose γ we have assumed to be the same as for the explosion products).

Crowley's experimental data for snow are given in Figure 2. The value of S is seen to increase more or less monotonically from about 0.3 at $\varsigma = 0.1$ to nearly

5 at $\varsigma = 1.4$. The theoretical curves for fixed α are arbitrarily computed assuming the snow, with initial density $\rho_{00} = 0.5$ g/cm^3, ended up at $\rho_0 = 0.76$ g/cm^3. The snow, however, was not found in a compacted layer, as was the salt, but instead fell to the bottom of the spherical container. We speculate that the rapid increase in S (and *apparent* decrease in α) with increasing charge is due to a decrease in the impulse delivery time brought about by the compaction process. We note that equation (1) assumes that the shocked material collapses to a final density that does not depend on pressure, so that $(dP/d\rho)_0 \rightarrow 0$. If this condition is violated and, in particular, if the wave speed in the compacted material approaches or exceeds the particle velocity, the impulse delivery time will rapidly decrease and the wall stress will increase proportionally.

Vermiculite Buffers

The ambiguity in the solution of equation (1) for α is eliminated when Neals's experiments with vermiculite (exfoliated mica) are considered [3]. Using flash radiography, and charged electrical shorting pins, he showed that the compaction factor, ρ_0/ρ_{00} $(= (1-k)^{-1})$ is more or less constant over an order-of-magnitude variation in charge-to-buffer mass ratio. Figure 3 depicts the results. The experiments were conducted in spherical pressure vessels of varying size, as shown in the figure. Tests were also made with the spheres either filled with air or evacuated (to 0.001 atm).

The filled-in symbols represent the measured wall stress with the vermiculite as a buffer, and the solid curves the stress predicted using equation (1). The observed behavior is similar to that observed with the snow in that S appears to increase more or less monotonically with ς; also α is roughly unity at the low ς limit. Note, however, that the abscissa scale in Figure 3 is very much magnified in comparison with Figure 2, so that at $\varsigma = 1.4$ (the upper snow limit, where $S \approx 5$) $S \approx 1.4$, comparable to the value for salt in Figure 1.

The dashed curve, labeled air blast theory, was calculated using equation (3), except that S_V was determined from the tests made with the evacuated spheres. The shaded vertical region on the right-hand side of Figure 3 shows the range of S_V for these shots; the average value, based on 5 tests, was 2.37. Using this value for S_V to calculate S_A is seen to give quite good agreement with the experimentally determined values of the latter, represented by the hollow symbols in the figure.

CONCLUSION

The impulse delivered to the walls of a vessel containing an explosion will increase if material is placed between the walls and the charge. If the impulse application time is small compared with the eigenperiod of the vessel, the wall stress will increase in direct proportion to the impulse. Conversely, if the application period can be extended beyond half the eigenperiod, the peak stress will be proportional to the ratio of the impulse to the delivery period. With powder or granular buffers, it is possible for the delivery period to increase faster than the impulse as the buffer mass is increased. This is the reason why certain powders, or porous materials, can provide stress reduction even below that observed by evacuating the space between the walls and the explosive.

If the buffer material is to serve as an effective mitigator, it must collapse on shock loading to a final density that depends only weakly on pressure; the criterion is that the wave speed in the material that impacts the wall must be small in comparison with the impact (particle) speed. This behavior apparently occurs with salt, at least for modest values of the charge parameter (ς), but to a lesser extent with snow under the same conditions. The vermiculite data are comparable to the salt in the ς region where the two overlap; with increasing explosive, however, the vermiculite appears to behave like the snow and its effectiveness as a mitigator rapidly diminishes.

It is also clear that once the wave speed criterion is seriously violated, the use of a powder buffer will result in a higher wall stress than if only air filled the space between walls and charge. For snow, the crossover point appears to occur at $\varsigma \approx 1$ whereas for vermiculite not until $\varsigma \approx 4$. Over the range investigated ($\varsigma(\max) = 1.1$), the performance of the salt did not appear to degrade with ς; the peak stress was at least 3 times less than observed with air at $\varsigma = 0.7$ and 7 times less at $\varsigma = 0.1$.

Salt (and also carbon) appears to dissipate significantly less energy than would be predicted with the conventional snowplow model. The fractional dissipation parameter, α, used to measure the discrepancy was inferred to be 0.4 - 0.6 over the entire range of ς in the salt experiments. The same range of α was determined for carbon, albeit at much higher ς [1]. The reason for this behavior is thought to be connected to resistance to deformation of the individual powder grains in the sense of dynamic pore closure [4]. In this connection, it should be remarked that, although the mechanism here is not well understood, it appears to be rate independent since the the carbon experimental results scale approximately over a six-fold change in linear dimension. Energy dissipation accompanying shock compression of porous bodies has been shown analytically to be rate independent whenever the shock pressure does not exceed the yield strength of the (rigid) matrix material [5].

REFERENCES

1. L. A. Glenn, "Explosive containment with spherically-tamped powders", J. Appl. Phys. (submitted); Lawrence Livermore National Laboratory preprint UCRL-93955, February 1, 1986.

2. G. G. Chernyi, "The problem of a point explosion", Dokl. Akad. Nauk SSSR, **112**, 213-216 (1957).

3. T. R. Neal, "Explosive containment", Proceedings of the VIIth AIRAPT Conference on High Pressure Science and Technology, Le Creusot, France, July 30-August 3, 1979, vol. 2, 1077-1079.

4. S. Z. Dunin and V. V. Surkov, "Dynamics of the closing of pores at the shock wave front", Prikl. Mate. Mekh., **43**, 550-558 (1979).

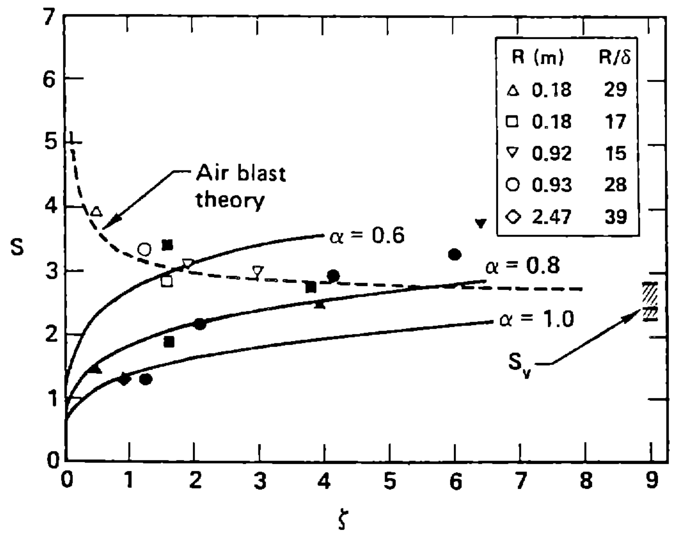
5. S. Z. Dunin and V. V. Surkov, "Effects of energy dissipation and melting on shock compression of porous bodies", Prikl. Mekh. Tekh. Fiz., **23**, 123-134 (1982).

CAPTIONS

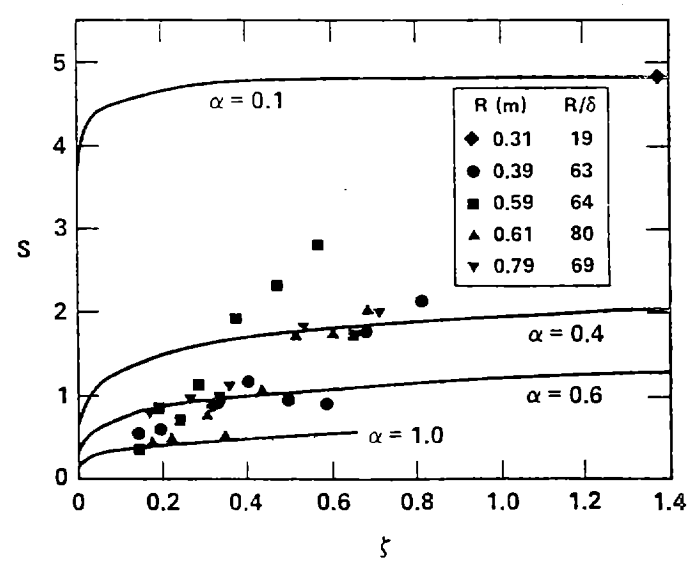
FIG. 1 Normalized peak wall stress as a function of the charge parameter for the experiments with granular salt (filled-in symbols). These are contrasted with experiments in the same pressure vessels, the space between the walls of which and the charge being filled with air.

FIG. 2 Normalized peak wall stress as a function of the charge parameter for the experiments with "snow".

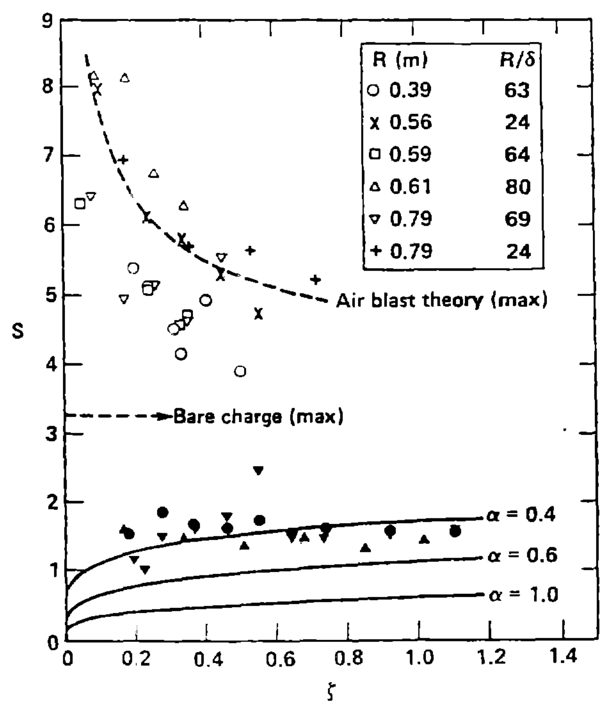
FIG. 3 Normalized peak wall stress as a function of the charge parameter for the experiments with vermiculite [3] (filled-in symbols). Hollow symbols identify contrasting air experiments. The shaded vertical region at the right indicates the bounds on the stress observed in the bare-charge (evacuated vessel) experiments.



R (m)
R/δ
0.18
29
0.18
17
0.92
15
0.93
28
2.47
39
Air blast theory
α = 0.6
α = 0.8
α = 1.0
S
ζ
S_v



α = 0.1
R (m) R/δ
0.31 19
0.39 63
0.59 64
0.61 80
0.79 69
α = 0.4
α = 0.6
α = 1.0
S
ζ
0 0.2 0.4 0.6 0.8 1.0 1.2 1.4
0 1 2 3 4 5


R (m) R/δ
○ 0.39 63
x 0.56 24
□ 0.59 64
△ 0.61 80
▽ 0.79 69
+ 0.79 24
Air blast theory (max)
Bare charge (max)
α = 0.4
α = 0.6
α = 1.0
S
ζ